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DOI: https://doi.org/10.1080/01694243.2019.1611008

Originally published at:
Schwendimann, Anita; Özcan, Mutlu (2019). Fatigue and fracture resistance of minimally invasive ceramic and resin composite veneers with different designs bonded adhesively to severely eroded teeth. Journal of Adhesion Science and Technology, 33(15):1715-1728.
DOI: https://doi.org/10.1080/01694243.2019.1611008

Fatigue and fracture resistance of minimally invasive ceramic and resin composite veneers with different designs bonded adhesively to severely eroded teeth

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Short title: *Fatigue resistance of ceramic and composite veneers*

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Abstract: This study evaluated the load bearing capacity of minimal invasive restoration alternatives on severely worn teeth after cyclic loading. Sound human maxillary incisors (N=72, n=9 per group) were randomly divided into nine experimental groups to receive one of the following restoration types: Group 1: Intact tooth, Group 2: Direct resin composite, Group 3: Lingual: Indirect resin composite, Labial: Ceramic veneer with lingual overlap, Group 4: Lingual: Indirect resin composite with lingual overlap, Labial: Ceramic, Group 5: Lingual: Direct composite, Labial: Ceramic, Group 6: Lingual: Feldspathic Ceramic, Labial: Feldspathic ceramic, Group 7: Lithium disilicate crown, Group 8: Metal-ceramic crown. Teeth were prepared simulating erosion/wear conditions. Specimens were subjected to cyclic loading (1.200.000 cycles, 5-55°C) and then loaded to failure from the lingual surface at 105° inclination (1 mm/min). Data (Newton) were analyzed using one-way ANOVA, Tukey`s tests and Weibull moduli were calculated (α=0.05). Significant differences were observed between the groups for the initial (p=0.006) and maximum fracture load (p=0.002). Group 3 (55±36) presented significantly lower initial fracture load compared to other groups (79±35-134±36) ($p<0.05$). When maximum fracture load is considered, control group (1) (602±355) and from restored groups 2 (449±144) and 4 (495±291) showed significantly higher results ($p<0.05$). Weibull modulus for the maximum fracture load was the highest for Group 2 (m=3.47) among all groups (m=1.61-4.18). Groups 2, 3, 6 presented the highest incidence of repairable failures. Based on the results, severely worn teeth could be restored with lingual direct resin composite and labial veneering with indirect resin with overlap.

Keywords: Erosion; Laminates; Minimal invasive; Static loading; Veneers; Wear.

Introduction

In recent years, dental erosion has become a major cause for the loss of mineralized tooth structure with a prevalence of up to 53.8% of the population between 18 and 35 years old [1-3]. Dental erosion or erosive tooth wear is the result of a pathologic, chronic, localized loss of dental hard tissues that is chemically etched away from the tooth surface by acid and/or chelation without bacterial involvement [2]**.** This type of demineralization could be caused by either extrinsic acid as a consequence of erosive diet or by intrinsic aetiology such as anorexia and bulimia nervosa or gastric reflux [4,5].

Severely worn anterior dentition requires restorations not only to restore aesthetic appearance but also to prevent further substance loss resulting in loss of vertical dimension. Typically, severely worn teeth are restored with full-coverage crowns, either made of porcelain fused to metal (PFM) or all-ceramic materials without metal framework where the latter provides better optical results than their metal-ceramic counterparts [6]. Both treatment modalities present survival rates of 95.6% after 5 years clinical function [7] and 97.4, 94.8 and 95.5% after 5, 8 and10 years, respectively [8]. Crowns could be considered invasive restoration options since they require four times more substance removal compared to minimal invasive resin composites or ceramic veneers [9]. Today, the possibility of etching and conditioning enamel and dentin and the introduction of resin based materials made it possible to restore teeth in a less invasive fashion. Direct or indirect minimal invasive options made of resin based composites, various ceramics or a combination of both, require different types of preparations [10]. While in some situations no preparation is required, in others minimal enamel/dentin removal would be sufficient to adhere resin or ceramic veneers. Both direct and indirect restoration options, deliver similar adhesion results on tooth substance when conditioned accordingly [11].

Survival rates of resin composite materials are limited from 3 to 6 years observation time [12-15]. One clinical study presented 10 year survival rates for anterior resin composite restorations with 58.9% being less than with metal-ceramic crowns (70.3%) [16]. On the other hand, anterior teeth could be restored with ceramic veneers in a minimal invasive approach [17-19]. Failure rates of such veneers made of feldspathic ceramics were reported to be less than 5% at 5 years and 5 to 35% for 10 to 13 years, respectively [20-24]. Type of preparation [25] and dentin exposure affects the long term survival rate of ceramic veneers [25] while material type (feldspathic or glass-ceramic) did not show significant difference when 5 years survival and complication rates were considered [26]. However, failures in the form of fractures constitute up to 50% of the failures according to the practice based evidence [27].

One other clinical protocol in restoring worn anterior teeth is the so called “sandwich approach” where primarily the palatal substance loss is restored for anterior guidance, using direct or indirect resin composite to the level of former tooth anatomy and vertical dimension [28]. Although, performance of resin composite or ceramic veneers is investigated [22,29], to date mechanical durability of sandwich approach has not been studied after fatigue conditions with a focus on the preparation type and material type combinations, making clinical decision complicated between invasive and less invasive therapy options. The amount of remaining structure certainly affects the stability of teeth. However, minimal invasive options based on different modalities of veneering techniques and materials in a sandwich design has not been investigated [30].

The objectives of this study therefore were to compare the fracture strength of different treatment modalities with and without sandwich design for restoring severely worn anterior teeth. The null hypothesis tested was that all restoration types and materials used would not show statistically significant difference in terms of initial and final fracture strength.

Materials and Methods

The brands, types, manufacturers and chemical compositions of the materials used in this study are listed in Table 1. Experimental workflow is presented in Fig. 1.

Specimen preparation

Sound human maxillary central incisors (N=72) (length: 15 - 35 mm; width: 5 to 9 mm), free from restorations and root canal treatment were collected. All teeth used in the present study were extracted for reasons unrelated to this project. Written informed consent for research purpose of the extracted teeth was obtained by all donors prior to extraction according to the directives set by the National Federal Council. Ethical guidelines were strictly followed and irreversible anonymization was performed in accordance with State and Federal Law [31,32]. After tissue remnants were removed with an ultrasonic scaler (Piezon Master 400, EMS, Switzerland) and teeth were stored in 0.5% Chloramin T at 5°C for 4 months until the experiments. After classifying the teeth based on their coronal dimensions (width and length) and root length, they were randomly assigned to 8 groups. The teeth with labial area less than 50 mm^2 were excluded.

The roots of the teeth were embedded in a polyvinyl chloride (PVC) mould using auto-polymerizing acrylic resin (Scandiquick, Scandia, Hagen, Germany) up to 1 mm above the mid-facial extent of the cemento-enamel-junction (CEJ). Impressions of the intact teeth were made using silicone (Optosil, Lab Putty, Heraeus Kulzer, Hanau, Germany) and cut in the labio-lingual direction. The silicone keys were used for controlled tooth preparation and used as reference for restoring the teeth to their original tooth shape and dimensions.

Simulation of erosive wear

Except for the control group (Group 1), coronal length of each tooth was shortened 3 mm from incisal resulting in coronal length longer than 2 mm for all teeth and preparation was made on the lingual side simulating substance loss through erosive wear [28]. Palatal reduction was performed using a diamond wheel (15 mm x 3 mm). Initially, using a diamond round bur with 1.5 mm diameter an indentations were created at three positions on the palatal area that served as marks for reduction control. This procedure resulted in standardized substance loss with complete dentin exposure (Figs. 2a-d).

Individual tooth preparations and restorations were as follows for each indication in Groups 2 to 8 (Figs. 3a-h):

Tooth preparations and restorations

Group 1: Intact teeth received no preparation and acted as the control group.

Group 2: Preparation was made on the labial surface in enamel with 1.5 mm width and minimal enamel bevel on the palatal and approximal sides. After etching with 37% H_3PO_4 for 60 s, the enamel surface was conditioned using etch-and-rinse adhesive system (Syntac Classic, Ivoclar Vivadent, Schaan, Liechtenstein) (Table 2). The teeth were reconstructed to their former shape by the silicone index as a reference, incrementally using resin composite (Empress Direct, Shade A3 Enamel, Ivoclar Vivadent) [33]. Each increment was photo-polymerized for 20 s using an LED polymerization device (Bluephase, Ivoclar Vivadent, light intensity: 1100 mW/cm^2) from a distance of 2 mm. Final restorations were polished with silicon impregnated rubber brushes (Astropol, Ivoclar Vivadent).

Group 3: In this group, lingual surfaces of the teeth were (0.7 mm) prepared and labial surfaces were reduced 0.5 mm in the enamel only with overlap lingually, while the incisal preparations were in dentin. For each tooth, models were obtained made of dental stone (Fujirock, GC, Tokyo, Japan). After isolating them with separation medium (Iso-K, Candulor, Glattpark, Switzerland), indirect resin composite veneers were processed using a highly filled polymeric material (G.aenial, GC, Tokyo, Kuraray) in a laboratory polymerization device (Heraflash, Hereaus-Kulzer, Hanau, Germany) for 120 s. The cementation surfaces were silica coated (30 µm SiO_2, CoJet, 3M ESPE, St. Paul, USA) at 2 bar pressure from a distance of 10 mm for 10 s, silanized (Monobond Plus, Ivoclar Vivadent) and allowed to react with the surface for 60 s. Thereafter, adhesive resin (Heliobond, Ivoclar Vivadent) was applied and the indirect composite veneers were cemented on the lingual side using dual-polymerized resin cement (Variolink II, Ivoclar Vivadent) that was then photo-polymerized from 5 different directions (labial, mesial, distal, occlusal, lingual). Impression was made from lingually veneered teeth and casts were made using a phosphate-bonded refractory die material

(Orbit Vest, GC). Labial veneers were made of feldspathic ceramic (Shade D A3 and S060, Creation, Cendres Métaux, Biel, Switzerland) and sintered. After removing the investment material from the ceramic surfaces by air-abrasion (30 μm SiO_2, CoJet), they were finished, polished and glazed. Subsequently, labial enamel surfaces were etched with 37% H_3PO_4 for 60 s, and conditioned using the adhesive system (Syntac Classic). Feldspathic ceramic veneers were etched with 5% hydrofluoric acid (IPS Empress Ceramic Etching Gel, Ivoclar Vivadent) for 60 s and ultrasonically cleaned (Vitasonic, VITA Zahnfabrik, Bad Säckingen, Germany) for 1 min in distilled water. Then adhesive resin was applied and ceramic veneers were adhesively cemented on the labial surface using the same materials and protocol described for the indirect resin composite veneers.

Group 4: In this group, lingual and labial veneer materials, cementation protocols were identical as in Group 3 except that ceramic veneer did not overlap lingually and lingual backing was only restored with indirect resin composite veneer.

Group 5: In this group, labial veneer material, cementation protocols were identical as in Group 4 except that lingual backing was only restored with direct resin composite incrementally (IPS Empress Direct, Ivoclar Vivadent) as in Group 2.

Group 6: Circumferential preparations of 0.6 mm in depth were made in enamel. Two-piece feldspathic veneers were processed, conditioned and cemented on the lingual and subsequently on the labial surfaces as described in Group 3.

Group 7: Circumferential preparations of 1.2 mm in depth were made on the teeth. Crowns made of lithium disilicate all-ceramic and cemented adhesively as described in Group 3. Etching duration with 5% hydrofluoric acid was 20 s.

Group 8: Preparations were similar as described in Group 7 but the crowns were made of metal-ceramic and cemented using conventional glass ionomer cement (Ketac Cem, 3M ESPE). Metal frameworks in this group were made of high gold alloy (Esteticor Special, Cendres & Métaux) and the venering from feldspathic ceramic (Creation, Cendres & Métaux). Prior to cementation, the intaglio surfaces of the crowns were air-abraded (30 µm SiO_2, CoJet) and ultrasonically cleaned for 1 min in distilled water.

Aging, fracture test and failure analysis

After cementing, the specimens were subjected to cyclic loading (1.200.000 cycles, 50 N, 1.67 Hz, 5-55°C, distilled water) in a custom made chewing simulator (University of Zurich) where the load was applied to the incisal 1/3 of the teeth from lingual at a load angle of 105° with a steel sphere (diameter: 3 mm).

The specimens were then mounted in the jig of the Universal Testing Machine (Zwick ROELL Z2.5 MA 18-1-3/7, Ulm, Germany) at an angle of 105°. A 0.5 mm tin foil was placed on the tooth to avoid punctual loading and repositioning of the stainless steel loading cell. Loading was performed at a crosshead speed of 1 mm/min. Total failure was defined when 30% decrease was reached in the applied load.

Failure types were analyzed and classified as follows: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. Score 1a, and 2b were further classified irreparable and the other scores as repairable.

Statistical analysis

A sample size of 9 in each group was calculated to have more than 80% power to detect a difference in means of 200 N between groups with a standard deviation of 100 N using a two-group Satterthwaite t-test (SPSS Software V.13 for Windows, Chicago, IL, USA) with a 0.05 two-sided significance level.

Kolmogorov-Smirnov and Shapiro-Wilk tests were used to test normal distribution of the data. As the data were normally distributed, one-way ANOVA and Tukey`s tests were applied to analyze possible differences between the groups where the fracture strength (initial and maximum) was the dependent variable and restoration modalities (8 levels) independent variables. Paired comparisons were made using Kruskal-Wallis, Wilcoxon side ranked and Canaver and Holm post-hoc tests (α=0.05). Following Anderson-Darling tests, maximum likelihood estimation without a correction factor was used for 2-parameter Weibull distribution to interpret predictability and reliability of strength for initial and maximum fracture load (Minitab Software V.16, State College, PA, USA). P values less than 0.05 were considered to be statistically significant in all tests.

Results

Significant differences were observed between the groups for the initial (p=0.006) and maximum fracture load (p=0.002). Except for Group 3, mean initial fracture load was significantly lower than maximum fracture load in all groups.

Group 3 (55±36) presented significantly lower mean initial fracture load compared to those of the other groups (79±35-134±36) (p<0.05) (Table 3). When mean maximum fracture load is considered, control group (1) (602±355) and from restored groups 2 (449±144) and 4 (495±291) showed significantly higher results ($p<0.05$) compared to the other groups (219±156 - 404±122) ($p<0.05$).

Weibull modulus was the highest for Group 2 ($m=3.47$) among all groups ($m=1.61-4.18$) for the maximum fracture load.

Groups 2, 3 and 6 presented the exclusively repairable failures.

Discussion

This study was undertaken in order to compare initial and maximum fracture strength of different treatment modalities for restoring severely worn anterior teeth with and without sandwich technique after cyclic loading. Based on the results of this study, since significant differences were observed between the groups, for both initial and maximum fracture strength, the null hypothesis tested could be rejected.

Erosion or wear starting from lingual or labial surfaces gradually overlaps the incisal parts of the teeth. Hence, treatment strategy varies depending on the severity and amount of tissue loss. In this study, different phases of such a treatment using ceramic and/or resin composite combinations were compared and both the initial and maximum fracture strength results were noted. The clinical implications of initial fracture strength is relevant to early failures of chipping or debonding that is commonly reported on veneers and crowns. Since the prognosis of the veneers was less favourable on dentin, in order to represent the worst case situation, lingual preparations were also made in dentin. Initial failures occurred at lower magnitudes of load when lingual preparations were made of indirect or direct resin composite compared to ceramics that were basically all repairable.

Similar level of adhesion of the resin cement to both substrates decreases the possibility of early delamination of one of the interfaces. This could then compensate for the low flexural strength or the elasticity modulus of the veneer material [34,35]. However, such results were derived from static loading conditions without cyclic loading. Depending on the percentage of fillers per volume, modern resin based composite materials typically have elasticity moduli between 6 to 15 GPa [36]. The indirect resin composite used in this study had elasticity modulus of 6 to 8 GPa according to the manufacturer, being significantly lower than that of feldspathic ceramic (60-70 GPa) and pressed lithium disilicate (96 GPa) [36]. Although information in this regard was not available for the direct resin composite, the non-significant difference between groups 2 and 4 indicates that both resin materials had comparable stiffness. In fact, polymerization under heat and pressure in laboratory processed resin composites show higher degree of conversion [37] but this does not necessarily increase their flexural strength [38] compared to those of direct resin composites [39]. Furthermore, during cyclic loading in distilled water, water sorption of the resin based materials could be expected yielding to similar initial fracture strength results. On the other hand, ceramic materials with their higher modulus of elasticity were claimed to transfer less stress to the tooth structures compared to resin composite restorations [40-42]. However, this property could also result in cohesive fracture of the material in ceramic overlapping veneers, which was evident in this study.

An incisal reduction was recommended in order to distribute the load more evenly and expose the veneer material to lesser stress levels [42]. Initial mean fracture strength was significantly lower in this study when the lingual overlap was made of ceramic. Nevertheless, the need for overlap is highly dependent on the level of dental tissue loss at the incisal edge [42] and besides better mechanical resistance, the choice of indirect resin composite on the lingual side results in less wear on the antagonist teeth [43,44]. For initial fracture load results, two piece ceramic veneers (m=4.24) followed by direct composites (m=3.44) presented higher Weibull modulus. The presence of dentin between two pieces of veneers possibly acted as crack stopper as opposed to one-piece ceramic crown and the good adhesion of direct composite without the cement layer assured less delamination and thereby more reliable strength.

Among invasive therapy options, namely the crowns made of lithium disilicate or metal-ceramic, the latter presented significantly higher results than those of minimal invasive options except direct composite build up (Group 2) and showed similar results compared to that of the intact teeth. When evaluating these results, it has to be noted that fractures in intact teeth were primarily in the enamel and veneering ceramic in the metal-ceramic crown group. Thus, the values obtained do not represent the fracture load needed to fracture the tooth itself or the metal framework of the metal-ceramic crowns. However, the metal-ceramic crown group presented less reliable modulus (m=2.82) compared to direct composite (m=3.44) when initial load was considered. This could be attributed to early fracture of the veneering ceramic. Although fracture strength was lower, the reliability in that respect was higher for lithium disilicate crowns (m=3.9) than metal ceramic for final fracture (m=3.58). The favourable bond strength of the resin cement to both the tooth and the intaglio surfaces of the lithium disilicate crowns [45], along with the higher elasticity modulus of this ceramic compared to feldspathic veneering ceramic on the metal could be considered as the reasons for this observation.

When veneering was performed with direct resin composite, not only higher initial and final fracture load values but also reasonably high Weibull moduli were noted. Fracture strength results were also comparable when lingual veneering was made by indirect resin composite instead of ceramic. Although indirect resin composites present lower elasticity modulus than that of feldspathic ceramic, the improved bonded interface in the tooth-cement-indirect composite especially after silica coating and silanization [33,46] could explain the high results in Group 4. This type of surface conditioning could be achieved either at the laboratory typically with 110 µm particles or at chairside with 30 µm. In an attempt not to affect the precision, the intaglio surfaces of the indirect resin were conditioned with the latter [47]. Building up the reconstruction with direct resin composite eliminates the cement layer and also reduces possible shrinkage and delamination of dentin-cement or cement-resin interfaces.

Fracture strength results should also be coupled with the failure type analysis. Except fractures that interfere with appearance that need replacement, in principle almost all failure types could be repaired with resin composites using the appropriate surface conditioning methods [47]. Among different failure types, root fracture is of lower or even non clinical relevance that could be due to pre-existing cracks in the extracted teeth or could have occurred during the cyclic loading in the chewing simulator. However, irreparable failures were more commonly observed in metal-ceramic crown group. The ductility of the metal framework possibly did not allow for final fracture and the load eventually fractured the root.

In this study, restored teeth were exposed to 1.200.000 cyclic loading. Static loading after limited number of cyclic loading alone could not single out the real effect of aging procedures. Therefore, future studies should incorporate the fatigue component in the study set-up in order to deduce more clinically relevant information considering the ultimate strength of the material to be tested after fatigue.

The acidic challenge encountered in the mouth, human saliva or artificial saliva as a medium were not practised in this study. Adhesion of the veneers may vary on demineralization dental tissues or in deeper levels of dentin that could be considered as a limitation of this study and should be studied in future investigations.

Conclusions

From this study, the following could be concluded:

1. Initial mean fracture load was significantly lower than final fracture load in all groups except for the group where lingual veneer was made of indirect resin composite and labial veneer from feldspathic ceramic with the overlap.

2. Among restored groups, veneering lingually and labially with direct resin composite or lingual veneering with indirect resin composite with the overlap showed significantly higher maximum fracture strength results compared to the other restoration alternatives.

3. Weibull modulus for maximum fracture load indicated the highest reliability of strength when lingual and labial veneering was made incrementally using direct resin composite.

4. Direct resin composite veneering both lingually and labially, labial veneering with ceramic but lingual veneering with either indirect resin composite or ceramic presented the highest incidence of repairable failures.

Clinical Relevance

Considering the fracture strength, reliability analysis and incidence of repairable failure types after fatigue loading, complete direct resin composite veneering or labial veneering with indirect resin composite including the overlap could be recommended for the restoration of severely worn teeth.

Acknowledgements

The authors acknowledge Mr. A. Trottmann, and G. Voce, CDT for their assistance with the specimen preparation.

Conflict of interest

The authors did not have any commercial interest in any of the materials used in this study.

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Captions to Figures and Tables:

Figures:

Fig. 1. Experimental sequence and allocation of groups depending on the material and restoration type.

Figs. 2a-d. Schematic drawing of **a)** intact tooth (control group), **b)** Incisal reduction of 3 mm to shorten all teeth and simulate incisal tooth wear, **c)** palatal removal of dentin, **d)** standardized tooth model for Groups 2 to 8.

Figs. 3a-h. Schematic drawings of reconstruction types and materials. **a)** Group 1: Intact tooth, **b)** Group 2: Direct Resin Composite, **c)** Group 3: Lingual: Indirect composite, Labial: Ceramic with lingual overlap, **d)** Group 4: Lingual: Indirect composite, Labial: Ceramic, **e)** Group 5: Lingual: Direct composite, Labial: Ceramic, **f)** Group 6: Lingual: Ceramic, Labial: Ceramic, **g)** Group 7: Lithium disilicate crown, **h)** Group 8: Metal-ceramic crown.

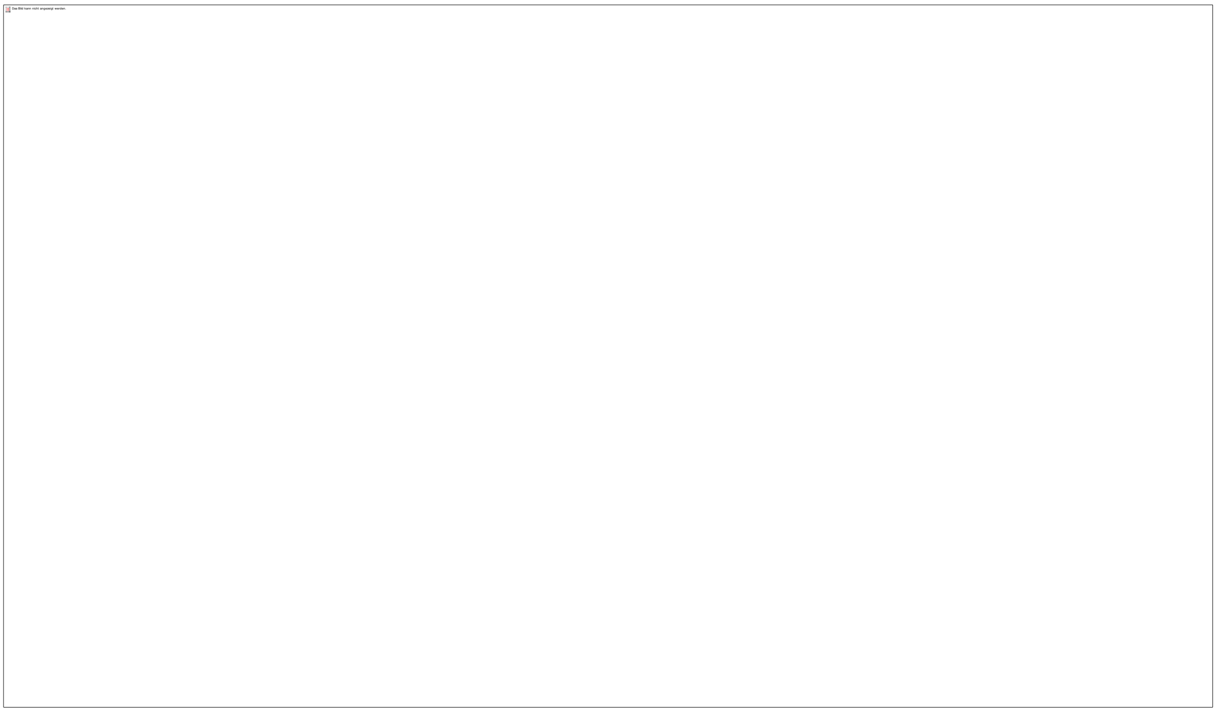
Tables:

Table 1 The product names, manufacturers, compositions and batch numbers of the materials used in this study.

Table 2 Cementation protocol employed on tooth substance and for the veneers and the crown materials in each experimental group.

Table 3 The mean initial and maximum fracture strength values (MPa ± standard deviations), Confidence Intervals (95%), Weibull modulus, distribution and frequency of failure types per experimental group analyzed after fracture strength test: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. *Score 1a, and 2b irrepairable and the other scores repairable. The same superscript lowercase letters in the same column and the same upper case leters in one row indicate no significant differences ($p<0.05$). For group descriptions see Figs. 1a-h.

Figures:



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Brand	Manufacturer	Chemical composition	Batch number

Tables:

Scandiquick	Scandia, Hagen, Germany	Polymethylmethacrylate	Liquid: 040125 Powder: 240125
Esteticor special	Cendres & Métaux, Biel, Switzerland	High-gold-alloy (77.3%), Ag, Pt , Pd, Cu, Fe, In, Ir, Se	0000 182002
Ceramicor	Cendres & Métaux	Phosphate-bonded investment compound, containing graphite	Liquid: 0000168251 Powder: 90801
Creation D (A3)	Cendres & Métaux	Feldspatic ceramic	9956
Creation S (060)	Cendres & Métaux	Feldspatic ceramic	9479
Glaze Liquid	Cendres & Métaux	Glazing liquid for ceramics	1064
Carat modelling liquid	Hager Werken, Duisburg, Germany	Modelling liquid for ceramics	604216
Opaquer	Cendres & Métaux	Opaquer mass	
G.aenial	GC, Tokyo, Japan	Mixture of urethane dimethacrylate, dimethacrylate co-monomers, fumed silica, fluoro-alumino-silicate, silica, strontium-glass, lanthanoid-fluoride, pigments and photo-activator/catalysts	0912211
Orbit vest	GC	Phosphate-bonded refractory die material	1010251
Optosil Lab Putty	Heraeus Kulzer, Hanau, Germany	C-polysiloxane Silicone	0174222
Syntac classic primer	Ivoclar Vivadent, Schaan, Lichtenstein	Acetone 25-50%, Triethylenglycoldimethacrylate 10-<25%, Polyethylenglycoldimethacrylate 3-<10%, Maleic acid (3-<10%)	N11162
Syntac classic adhesive	Ivoclar Vivadent	Polyethylenglycoldimethacrylate 25-50%, Glutaraldehyde 3-<10%	N11161
Heliobond	Ivoclar Vivadent	bis-GMA (50-100%),	N75604 (bond)

		Triethylenglycoldimethacrylate (25-50%)	
MonoBond Plus	Ivoclar Vivadent	Monomer: <1.5% Methacrylate, Phosphoric acid ester Solvent: Ethanol (96%)	P20536
VarioLink II	Ivoclar Vivadent	Dimethacrylates, inorganic fillers, ytterbiumtrifluoride, initiators, stabilizers and pigments	P22989
IPS Speed vest	Ivoclar Vivadent	Phosphate-bonded investment compound for ceramics	Liquid: HL3041 Powder: PL3060
IPS e.max press	Ivoclar Vivadent	Lithium disilicate press ceramic	N75604
IPS Empress Direct	Ivoclar Vivadent	Urethane dimethacrylate, tricyclodocane dimethanol dimethacrylate, bis-GMA, Ytterbium trifluoride, Ba-Al-fluorosilicate glass, prepolymer, pigments and catalysts	P34518
IPS Empress ceramic etching gel	Ivoclar Vivadent	5% Hydrofluoric acid	P26213
Total etch	Ivoclar Vivadent	37% H_3PO_4	N11162
Ketac cem	3M ESPE	Water, polycarboxylic acid, tartaric acid, glass powder, pigments and conservation agents	352671

Table 1. The brands, manufacturers, chemical compositions and batch numbers of the materials used in this study.

Groups	Adhesive / Cementation mode	Polymerization
2	Syntac Classic	Photo-polymerization for 20 s for each increment
3/4	Tooth: Syntac Classic	No polymerization
	Indirect Composite: Monobond Plus	
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
5/6	Tooth: Syntac Classic	No polymerization
	Ceramic: Monobond Plus	Reaction with the surface for 60 s
	Adhesive: Heliobond	No polymerization
	Cement: VarioLink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
7	Tooth: Syntac classic	No polymerization
	Ceramic: Monobond Plus	Reaction with the surface for 60 s
	Adhesive: Heliobond	No polymerization
	Cement: Variolink II translucent (low viscosity)	Photo-polymerization for 40 s from 5 directions
8	Ketac cem	Chemical polymerization

Table 2. Cementation protocol employed on tooth substance and for the veneers and the crown materials in each experimental group.

						Weibull modulus (m) (*95% CI*)			Failure type distribution (n)				
Groups	**Fracture Strength ($F_{initial}$) (Mean ± SD)**	***Min-Max* (*95% CI*)**	**Fracture Strength (F_{max}) (Mean ± SD)**	***Min-Max* (*95% CI*)**	**m ($F_{initial}$)**	***Scale***	**m (F_{max})**	***Scale***	**Score 1a/1b**	**Score 2a/2b**	**Score 3**	**Score 4**	**Repairable/ Irrepairable**
1	$134 \pm 36^{a,A}$	82-186 (105-164)	$602 \pm 355^{a,B}$	113-996 (489-769)	4.18	142.8	1.82	676.4	2/7	0/0	0	0	7/2
2	$77 \pm 28^{a,A}$	20-111 (49-105)	$449 \pm 144^{a,B}$	255-744 (317-581)	3.44	85.72	3.47	498.6	4/0	5/0	0	0	9/0
3	$55 \pm 36^{b,A}$	10-110 (27-83)	$219 \pm 156^{b,A}$	10-582 (87-350)	2.03	68.2	1.99	278.2	0/0	5/0	0	4	9/0
4	$115 \pm 74^{a,A}$	20-220 (87-143)	$495 \pm 291^{a,B}$	189-963 (363-627)	1.61	127.4	1.89	559.2	0/0	5/2	0	2	7/2
5	$79 \pm 35^{a,A}$	20-125 (51-107)	$319 \pm 155^{b,B}$	128-540 (187-450)	2.59	88.69	2.38	361.4	0/1	4/1	0	3	8/1
6	$100 \pm 31^{a,A}$	42-130 (72-129)	$285 \pm 109^{b,B}$	179-534 (153-417)	4.24	110.8	2.85	319.9	0/0	9/0	0	0	9/0
7	$116 \pm 40^{a,A}$	83-210 (88-144)	$320 \pm 97^{b,B}$	180-479 (188-452)	3.08	129.3	3.9	354.5	0/4	1/4	0	0	5/4

8	96 ± 40^{a,A}	19-143 (68-125)	404 ± 122^{a,B}	326-658 (272-536)	2.82	107.6	3.58	447.3	9/0	0/0	0	0	0/9

Table 3. The mean initial and maximum fracture strength values (MPa ± standard deviations), Confidence Intervals (95%), Weibull modulus, distribution and frequency of failure types per experimental group analyzed after fracture strength test: Score 1a-b: No visible fracture of the veneers with (1a) or without root fracture (1b), Score 2a-b: Cohesive fracture within the veneer material without tooth involvement (2a) or with tooth fracture (2b), Score 3: Only crack formation without debonding of the veneer, Score 4: Partial or total adhesive delamination of the veneer material from the tooth surface. *Score 1a, and 2b irrepairable and the other scores repairable. The same superscript lowercase letters in the same column and the same upper case leters in one row indicate no significant differences ($p<0.05$). For group descriptions see Figs. 1a-h.